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Muon Physics Working Group Summary & Questions Posed

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NuFact 2015 Rio de Janeiro, Brazil

Look Back to NuFact 13/14

Questions moving forward for 2014

- Three "Big" questions we want to address:
  - Expt: What is the ultimate $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ reach once $\mu N \rightarrow eN$ has set the limit.
    - What are the roles of the ratios of cLFV processes and other precision experiments at this point?
  - Beams: What are the beam specifications for muon physics? (our requirements)
    - Are these compatible with the NuFact?
    - Are there other options?
  - Theory: What else besides cLFV? EDMs?
    - What does theory tell us once we observe cLFV?
    - How do we relate our results to the models?

NuFact13-WG4 8/14/15 3

We understand the experiment design
- This generation
- And next

Many optimized designs that are starting into construction
- g-2, Mu2e, COMET, MEG2, Mu3e, DeeMe, etc…

Look Back to NuFact 13/14

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NuFact13-WG4 8/14/15 3

We know the beams we need:

- need highly sculpted pulsed beams (Mu2e, COMET)
- need DC beams (MEG, Mu3e)
- need ultra cold beams (J-PARC g-2)

These MAY be compatible with a new facility

- Cost

May be options

- cooled μ's + phase rot.

Questions Posed to NuFact 2015

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- How could a neutrino factory (and the supporting accelerator complex) be exploited to push our sensitivities for cLFV searches and precision measurements? Is there a secondary physics program that could be supported by such a complex which could address questions in both HEP and Nuclear Physics?
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Global Perspective

- What is the global picture that ties together "direct" and "indirect" for BSM physics?
  - What are the results from the LHC and B-Factories telling us?
  - How do we connect this sector's limits with the next generation of precision measurements?
  - Time scales?

A. Nehrkorn, CMS

Hints from the Energy Frontier

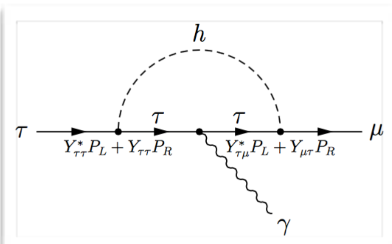
Introduction

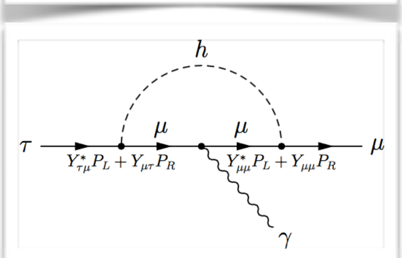
arXiv:1207.7235

- LFV couplings to the Higgs possible …
  - … if SM only valid to finite scale Λ
  - … in models with > 1 Higgs doublet (e.g., 2HDM)

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

- LFV Higgs couplings would allow processes like μ→e, τ→μ and τ→e via a virtual Higgs boson





- $\mathcal{B}$(H→eμ) < O(10^{-8}) @ 95% CL from searches for μ→eγ
- $\mathcal{B}$(H→eτ) < O(10%) and $\mathcal{B}$(H→μτ) < O(10%) @ 95% CL from searches for τ→e/μγ and μ/e g-2 measurements
- $\mathcal{B}$(H→e/μτ) < 13% @ 95% CL from theoretical reinterpretation of H→$\tau\tau$ search results from ATLAS

→ direct search very promising

Fermilab

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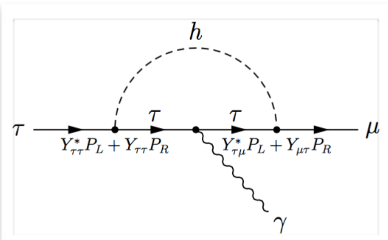

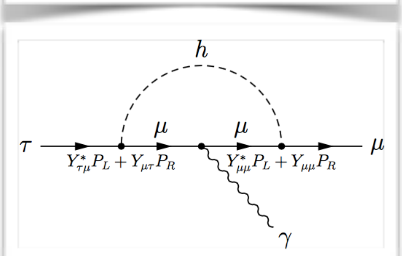

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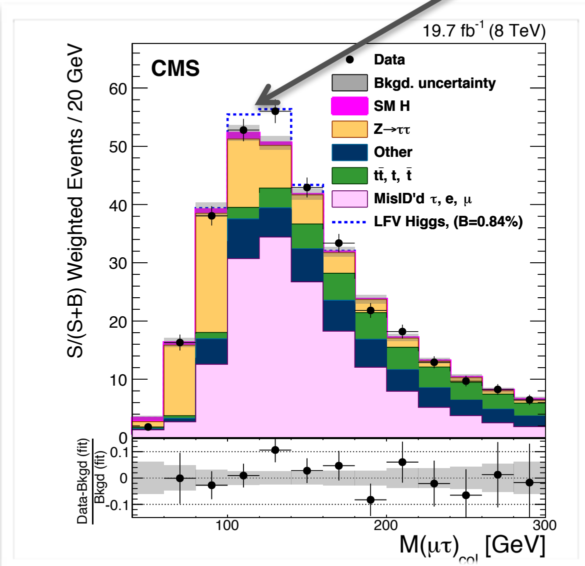
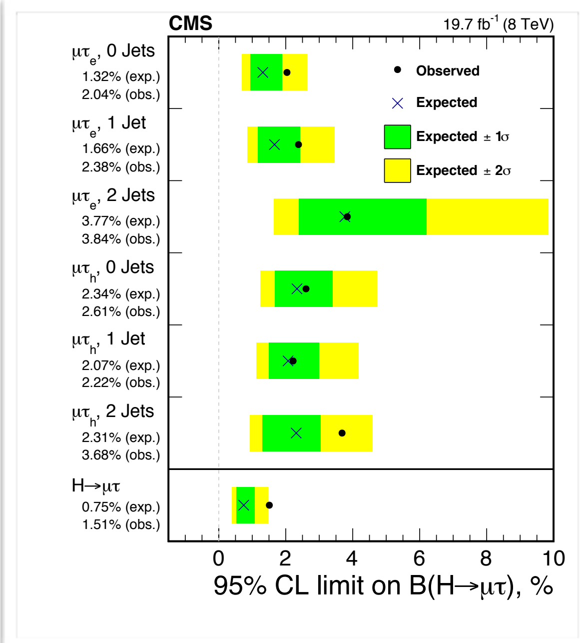
Hints from the Energy Frontier

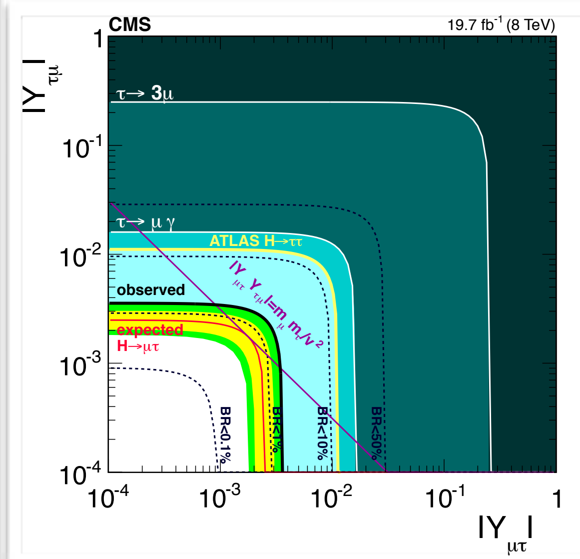
arXiv:1502:07400

Results

Excess in $H\to\mu\tau$ channel







$$\mathcal{B}(H\to\mu\tau)_{\text{best fit}} = (0.84^{+0.39}_{-0.37})\%$$

$$\mathcal{B}(H\to\mu\tau) < 1.51\%\ @\ 95\%\ \text{CL}$$

$$\sqrt{|Y_{\mu\tau}|^2+|Y_{\tau\mu}|^2} < 3.6\cdot 10^{-3}$$

C. Blocker, Atlas

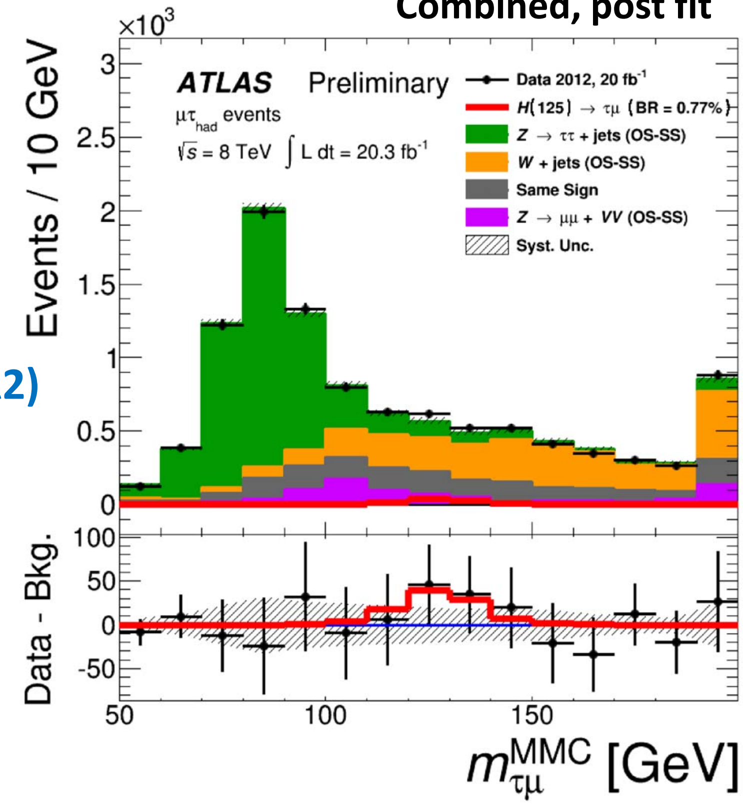
Hints from the Energy Frontier

Events with μ and hadronically decaying τ.

Use τ kinematics and missing Et to correct for undetected ν.

NEW!

Combined, post fit



Two signal regions

SR1: $m_T(\mu, E_T^{miss}) > 40$ GeV and
$m_T(\tau_{had}, E_T^{miss}) < 40$ GeV

SR2: $m_T(\mu, E_T^{miss}) < 30$ GeV and
$m_T(\tau_{had}, E_T^{miss}) < 60$ GeV

Dominant backgrounds are $Z/\gamma^* \to \tau\tau$ (SR2) and W + jets (SR1)

BR < 1.85% (95% CL)

Theory: BR < ~10% from $\tau \to \mu\gamma$ and $(g\text{-}2)_{e,\mu}$

No Confirmation from Atlas in $H\to\mu\tau$ channel

Limits from the Energy Frontier

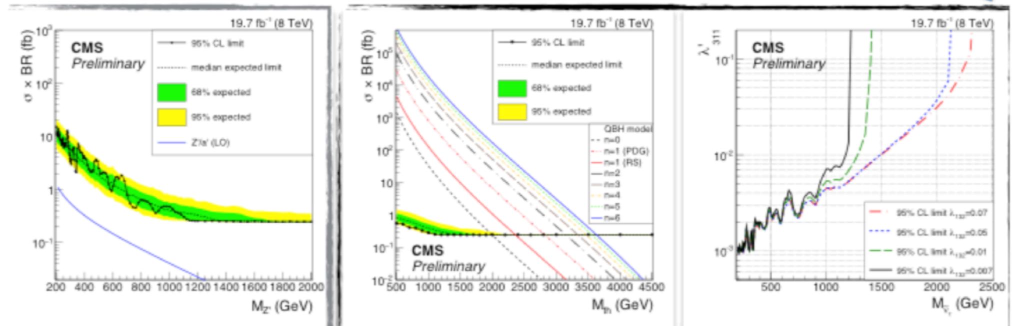
A. Nehrkorn, CMS

No evidence in
Z´ and Quantum Black Holes

LFV Decays of Heavy Resonances and QBHs

CMS-EXO-13-002

Results



- No sensitivity to Z', yet
- Need to gain one order of magnitude

Limits in terms of m < …

QBH

RPV SUSY

- … 1.99 - 3.63 TeV for n = 0 - 6
- … 1.21 (2.11) TeV for $\lambda_{132} = \lambda'_{311} = 0.01$ ($\lambda_{132} = 0.05$, $\lambda'_{311} = 0.1$)

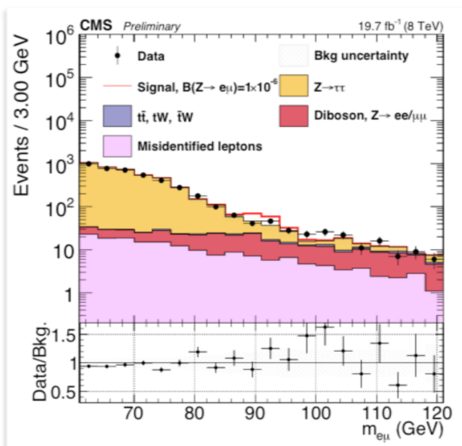
LFV in Z Decays

Results

- Count events in window around Z mass: (91 ± 3) GeV
- Background prediction of 83 ± 9
- Events found in data: 87
- Use CL$_S$ method to determine limit:

$$\mathcal{B}(Z \to e\mu)_{\text{expected}} < (6.7^{+2.8}_{-2.0}) \cdot 10^{-7}$$

$$\boxed{\mathcal{B}(Z \to e\mu)_{\text{observed}} < 7.3 \cdot 10^{-7}}$$

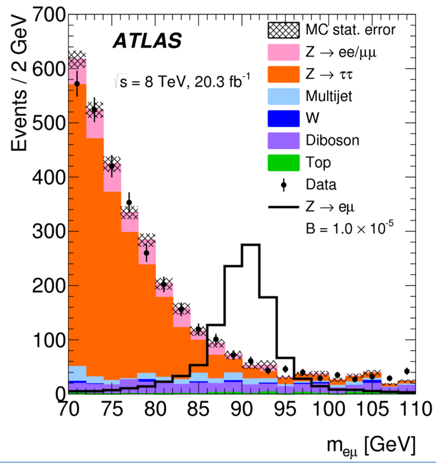


No evidence in
Z Decays

Limits from the Energy Frontier

Z → eμ

PRD 90, 072010 (2014)
arXiv: 1408.5774

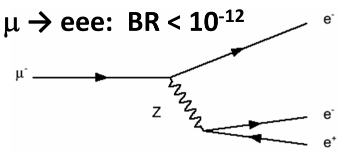


Fit to background + signal.

BR (Z → eμ) < 7.5 × 10^{-7} (95% CL)

LEP: BR < 1.7 × 10^{-6} (95% CL)

Limit inferred from
μ → eee: BR < 10^{-12}

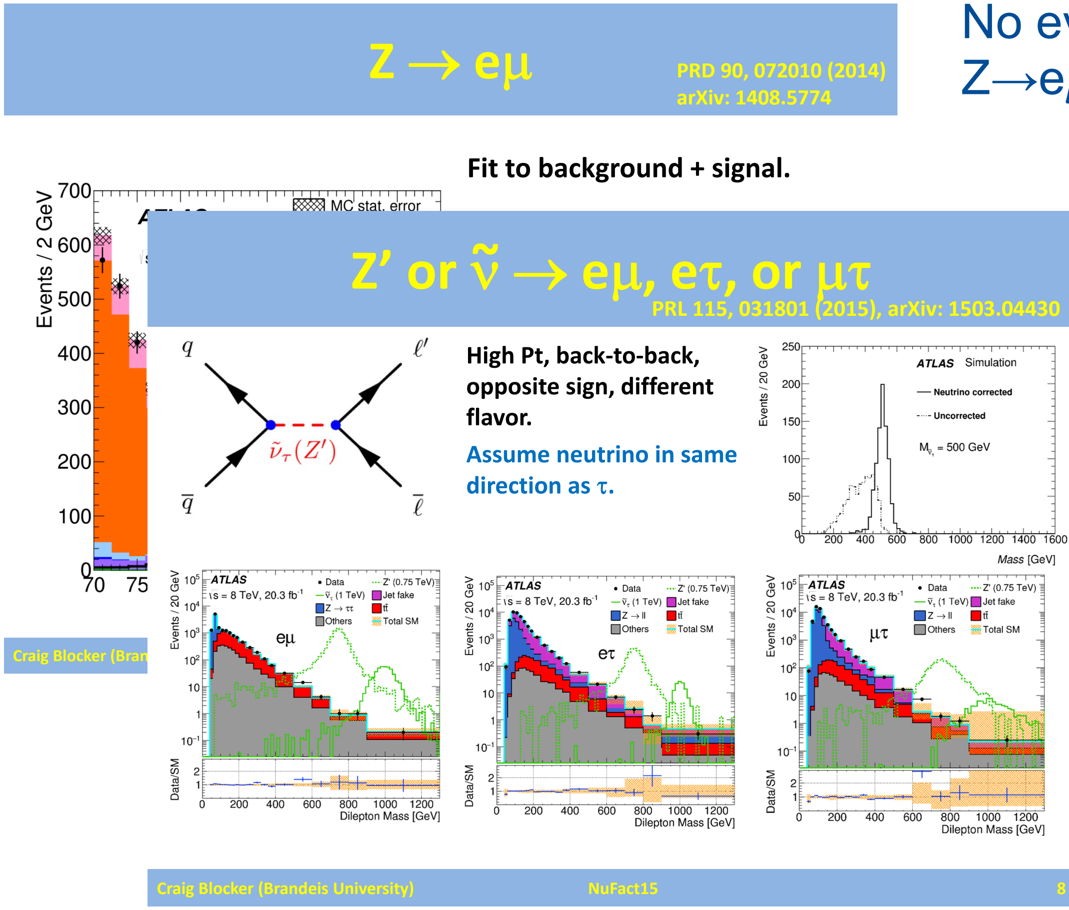


Craig Blocker (Brandeis University) NuFact15 7

No evidence in
Z→eμ

C. Blocker, Atlas

Limits from the Energy Frontier

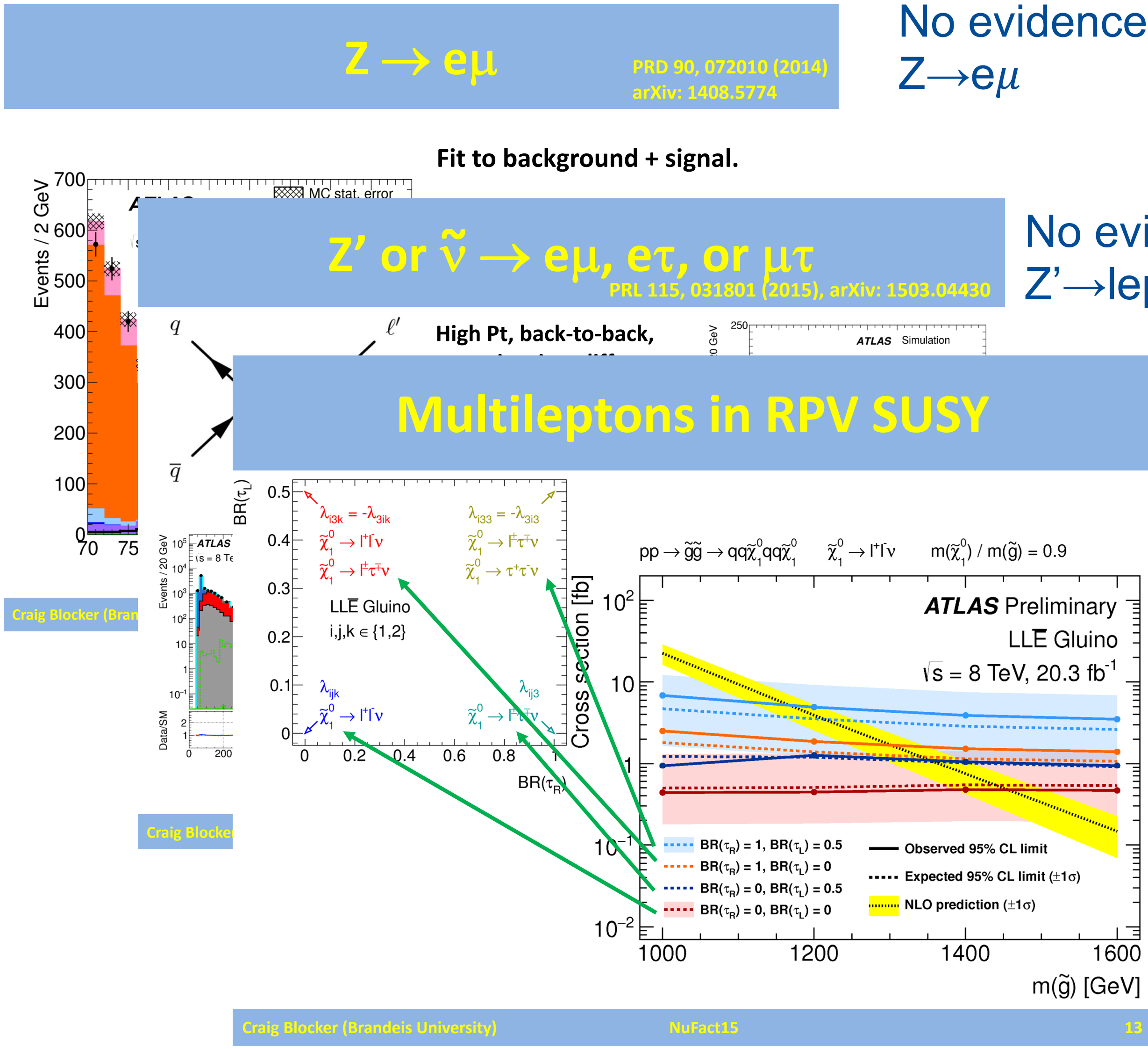


No evidence in Z→$e\mu$

No evidence in Z'→leptons

C. Blocker, Atlas

Limits from the Energy Frontier



No evidence in $Z \to e\mu$

No evidence in $Z' \to$ leptons

No evidence in Multilepton channels

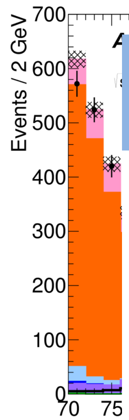
Limits from the Energy Frontier

C. Blocker, Atlas

Z → eμ
PRD 90, 072010 (2014)
arXiv: 1408.5774

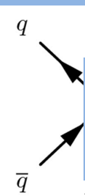
No evidence in Z→eμ

Fit to background + signal.



Z' or $\tilde{\nu}$ → eμ, eτ, or μτ
PRL 115, 031801 (2015), arXiv: 1503.04430

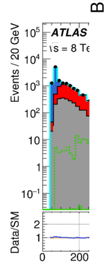
No evidence in Z'→leptons

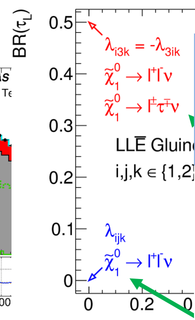


High Pt, back-to-back,

Multileptons in RPV SUSY

No evidence in Multilepton channels





Craig Blocker (Bran

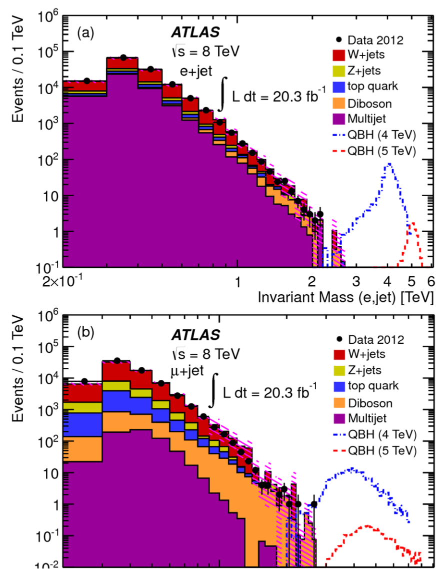
Craig Blocke

Craig Blocker (Brande

Black Hole → lepton + jet
PRL 112, 091804 (2014)

No evidence in QBH searches

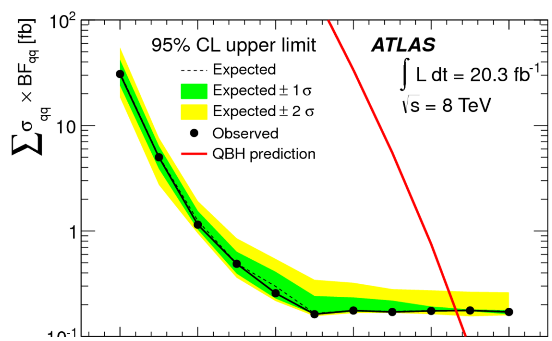
….



Quantum black holes predicted in low-scale gravity theories.

Expected to conserve angular momentum, charge, color but not other SM quantities.

Search for BH → ℓ + jet.



Fermilab

C. Cecchi, Belle II

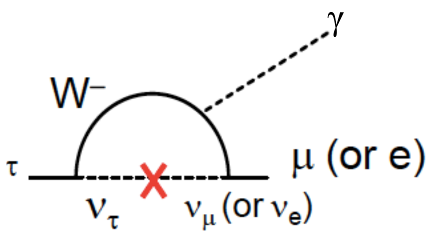
Limits from the B-Factories

- **Identical in flavor structure to μLFV channels**
- **Enhanced branching fractions due to τ mass**
- **Compare 10^{-7} for SUSY prediction to 10^{-14} – 10^{-11} prediction for $\mu \rightarrow e\gamma$**

Tau Lepton Flavor Violation

$$Br(\tau \to \mu\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2} \right)^2 < 10^{-40}$$

(X.Pham, EPJC8 513(1999))



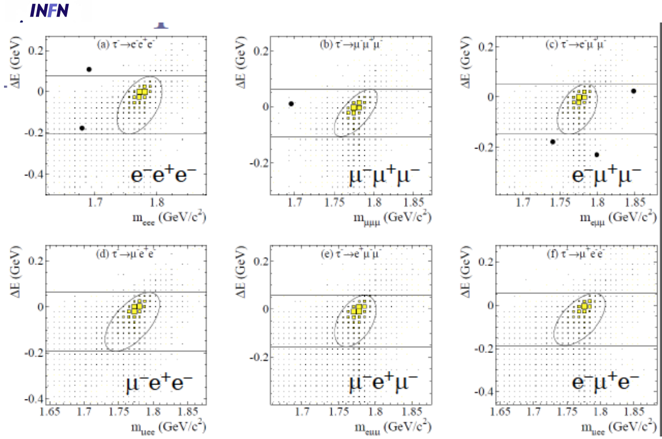
Ratio of Tau LFV decay BF: discrimination of NP models

JHEP 0705, 013(2007), PLB54 252 (2002)

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\left(\frac{\tau \to \mu\mu\mu}{\tau \to \mu\gamma}\right)$	$\sim 2 \times 10^{-3}$	0.06~0.1	0.4~2.3	~16
$\left(\frac{\tau \to \mu ee}{\tau \to \mu\gamma}\right)$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	0.3~1.6	~16
$Br(\tau \to \mu\gamma)$ @Max	$<10^{-7}$	$<10^{-10}$	$<10^{-10}$	$<10^{-9}$

C. Cecchi 4

Limits from the B-Factories

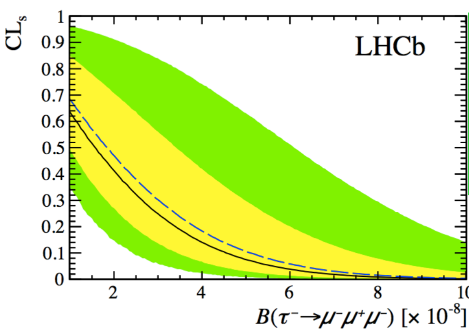


$\tau \to 3$ leptons

No evidence in $\tau \to 3\ell$

BELLE data set: 782 fb^{-1}
No events have been found in the signal region

Very good lepton ID → almost no bckgnd
Expected bckgnd events : 0.01 - 0.21



LHCb: 1 fb^{-1}@7TeV + 2fb^{-1}@8TeV
Br < 4.6 $\times 10^{-8}$ @ 90% C.L.
JHEP 02 (2015) 121

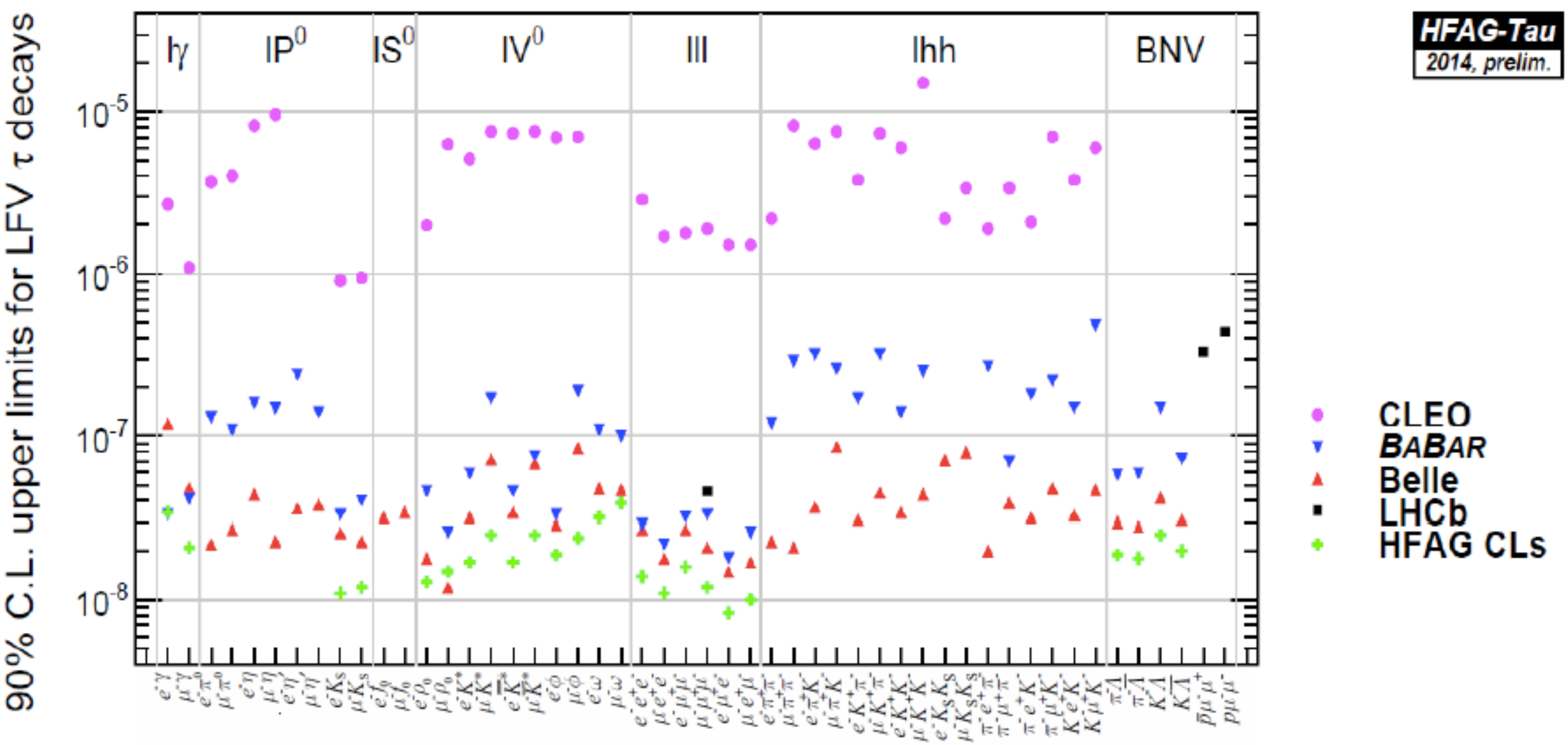
Mode	ε (%)	N_{BG}^{EXP}	σ_{syst} (%)	UL ($\times 10^{-8}$)
$e^-e^+e^-$	6.0	0.21±0.15	9.8	2.7
$\mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	2.1
$e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	2.7
$\mu^-e^+e^-$	9.3	0.04±0.04	7.8	1.8
$\mu^-e^+\mu^-$	10.1	0.02±0.02	7.6	1.7
$e^-\mu^+e^-$	11.5	0.01±0.01	7.7	1.5

Br < (1.5-2.7) $\times 10^{-8}$ @ 90% C.L.
(Phys. Lett. B687, 139 (2010))

C. Cecchi, Belle II

Limits from the B-Factories

Or any of 48 other decay channels….. (but look at the sensitivities!)



48 decay modes investigated – 100 x more sensitivity w.r.t. CLEO results
LHCb results on 3 leptons comparable to B-factories

Limits from the Energy Frontier

Atlas, Belle, CMS, others

- No clear evidence for LFV across MANY channels

- Current μLFV experiments already set limits on many channels beyond the LHC reach

- But…many channels are not constrained.

Future at the Energy Frontier

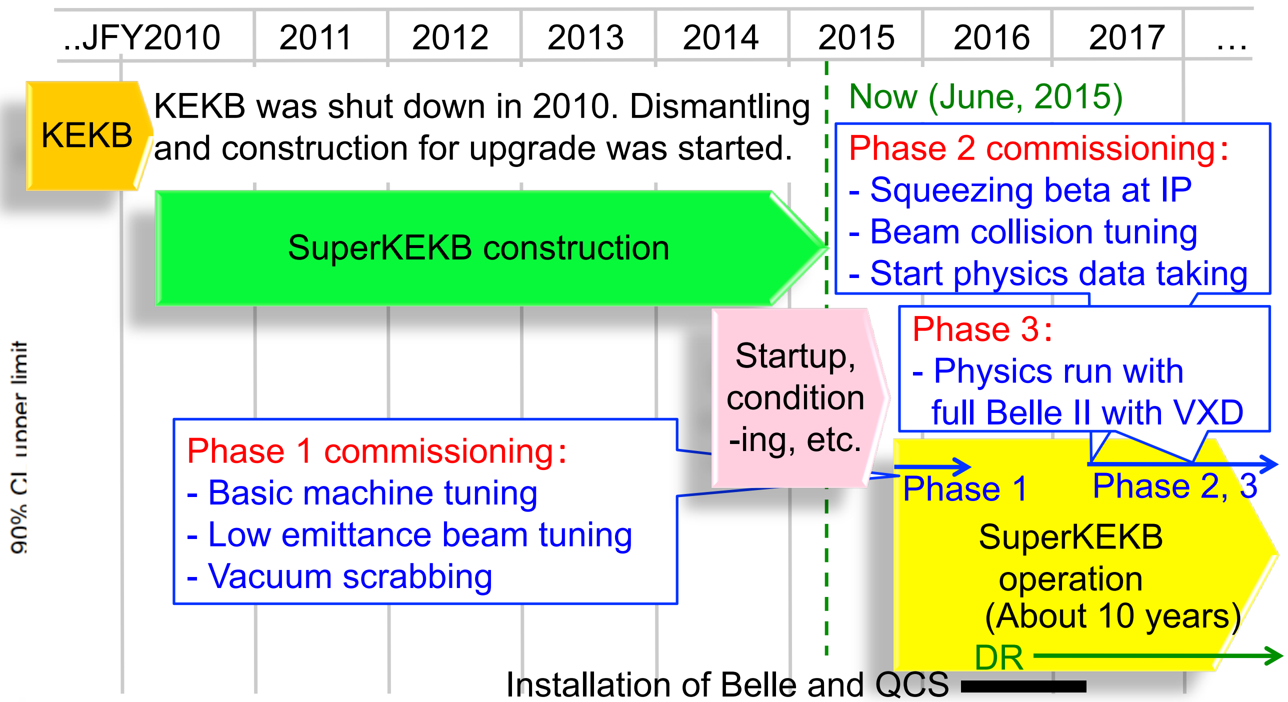
- 14 TeV

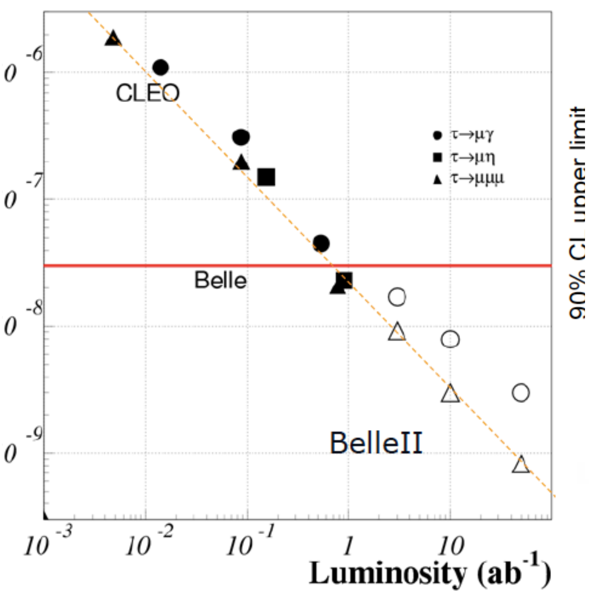
Drives the cross sections and all the sensitivities to BSM physics

Fermilab

Future of the B-Factories

✓ SuperKEKB construction is finished
✓ startup for Phase 1 are in progress.





The no-background regime improves as $1/\int L\,dt$
If there are background events, the improvement is $1/\sqrt{\int L\,dt}$

τ → μγ (no bckgnd free) expected limite O(10^{-9})
τ → μμμ (bckgnd free) expected limit O(10^{-10})

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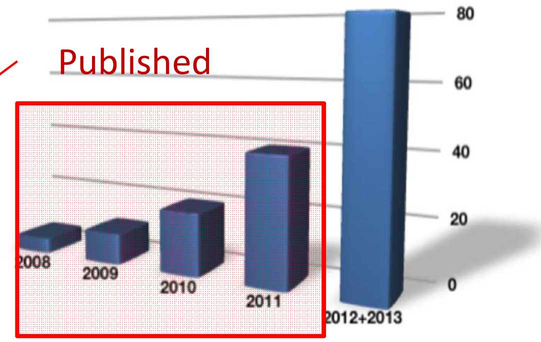
D. Grigoriev

$\mu \to e\gamma$ (MEG and MEG2)

Results

Phy. Rev. Lett. 110, 201801 (2013)

Data taking finished at 31.08.2013
Statistics is doubled compare to published



year	Nstop μ, $x10^{13}$	Sensitivity, $x10^{-13}$	Br, Upper limit (CL 90%), $x10^{-13}$
2009+2010	17.5	13	13
2011	18.5	11	6,7
2009+2010+2011	36.0	7.7	**5.7** (20 times better
All data (expected)	~80	~5	than MEGA)

Final result of analysis is expected by the end of 2015 with the improved analysis. The data are reprocessed now.

Fermilab

$\mu \rightarrow e\gamma$ (MEG and MEG2)

Results

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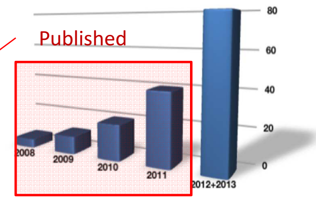

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Trying to improve the analysis techniques to get better sensitivity scaling than just √N as they double their data set

Improvement of the analysis

- Event reconstruction algorithm.
- Calibration procedures.
- Background rejection techniques.
  - recover positron tracks which cross the target twice (missing turn analysis)
  - Identify background γ-rays generated when a positron annihilates with an electron on some detector material (annihilation-in-flight (AIF) analysis)
  - refine the alignment procedure of the target and drift chamber system.

$\mu \rightarrow e\gamma$ (MEG and MEG2)

How the sensitivy can be pushed down?

- More sensitive to the signal...

high statistics

$$SES = \frac{1}{\boxed{R} \times T \times A_g \times \varepsilon(e^+) \times \varepsilon\,(gamma) \times \varepsilon(TRG) \times \varepsilon(sel)}$$

beam rate / acquisition time / geometrical acceptance / detector efficiency / selection efficiency

- More effective on rejecting the background...

high resolutions

$$B_{acc} \sim R \times \Delta E_e \times \boxed{(\Delta E_{gamma})^2} \times \Delta T_{egamma} \times \boxed{(\Delta \Theta_{egamma})^2}$$

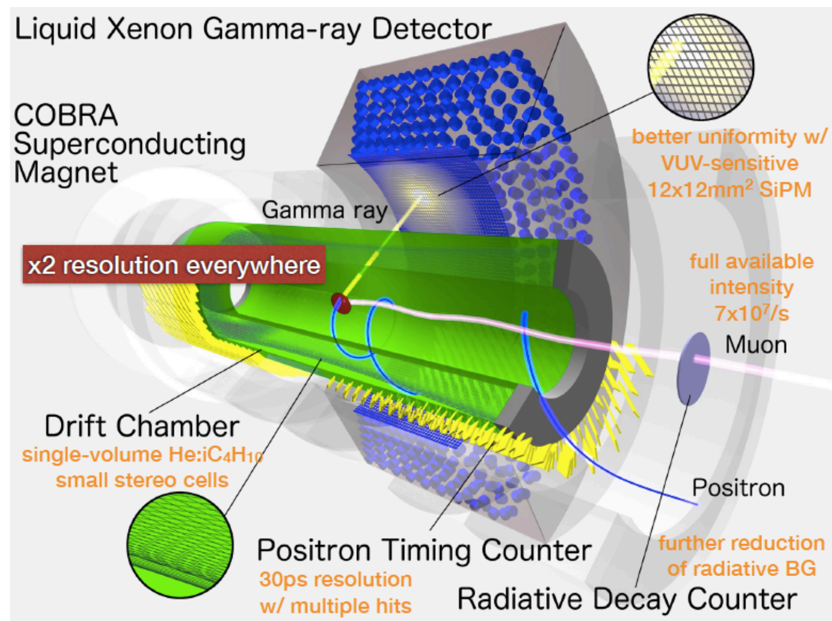
momentum resolution / Energy resolution / Relative timing resolution / Relative angular resolution

11

MEG2 focuses on improving energy and angular resolutions along with detector efficiencies to improve signal/background

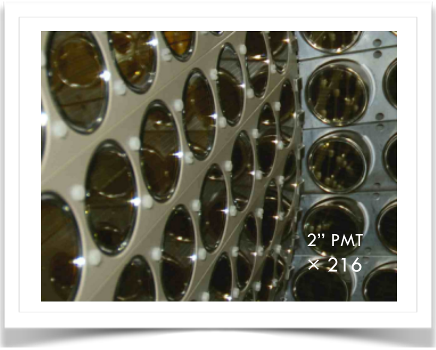
- Redesigned spectrometer
- Upgraded calorimeter

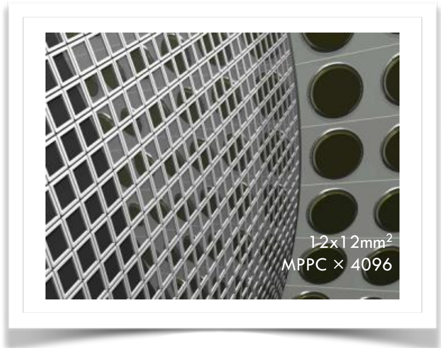
The MEGII experiment -3D view



$\mu \to e\gamma$ (MEG and MEG2)

The upgraded Liquid Xenon calorimeter



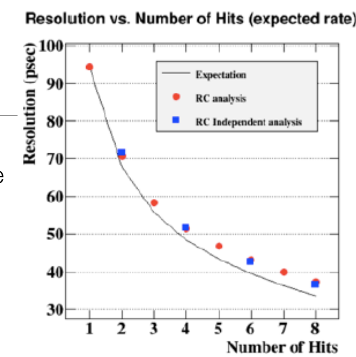


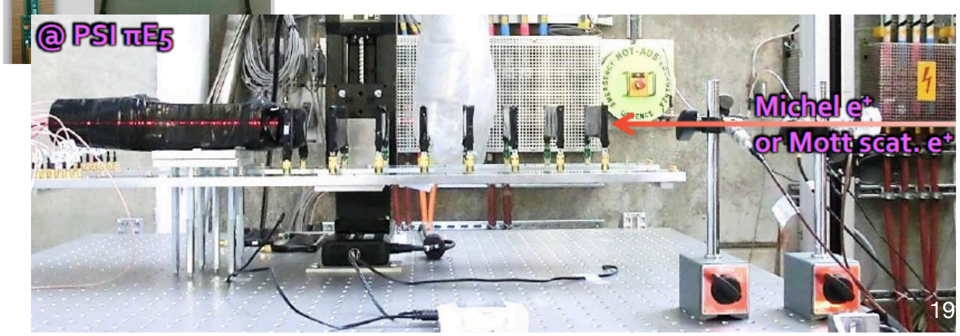
- Calorimeter → SiPM
- Higher density/eff dection

Re-designed timing counters lower timing res to 35 ps for pileup rejection

A new re-designed spectrometer: the pixelized Timing Counter (in numbers)

Timing resolution:
35 ps at the MEGII rate conditions





Goal is a 10x improvement in sensitivities to BR ~ 5×10^{-14}

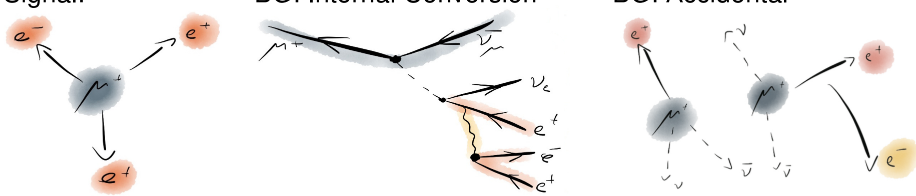
$\mu\to$eee (Mu3e)

R. Gredig

The Mu3e Experiment

- Mu3e is a dedicated experiment searching for $\mu^+ \to e^+e^-e^+$
- aimed sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$
- stopped muons per second: 10^9
- main background: $\mu \to eee\nu_e\nu_\mu$, with $\mathcal{B} = 3.4 \cdot 10^{-5}$ and accidentals

Signal: BG: Internal Conversion BG: Accidental

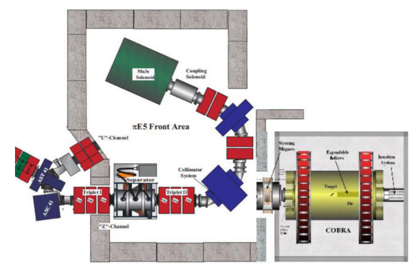


Signal:
- $\Sigma \vec{p}_i = 0$
- common vertex
- $p < 53$ MeV

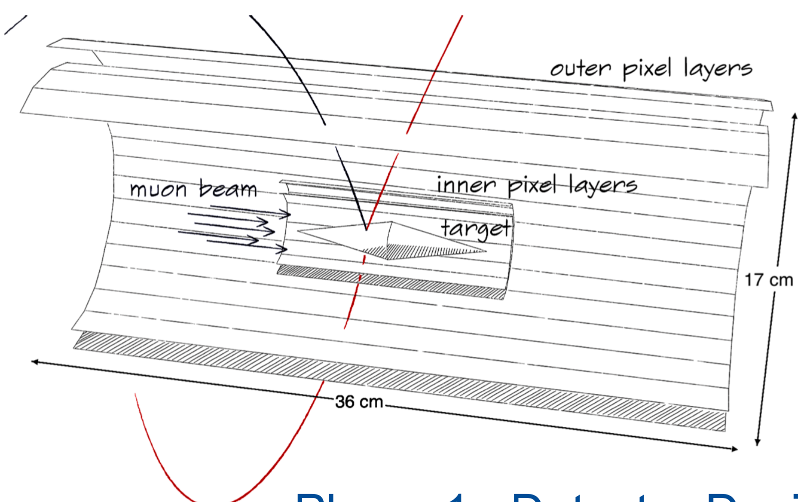
BG: Internal Conversion:
- $\Sigma \vec{p}_i \neq 0$
- common vertex

BG: Accidental:
- non common vertex
- not in coincidence

Beamline Design

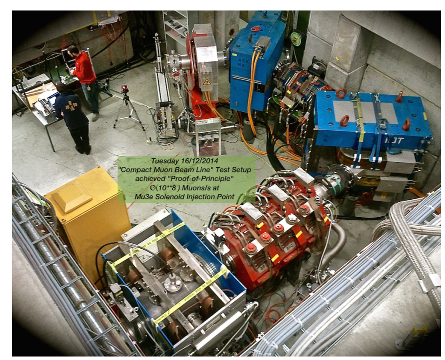


- muon beamline at PSI
- low energy DC beams
- πE5 beamline: $\sim 10^8$ 28 M
surface muons
  - shared with MEG
  - works for Phase I → ap
- HiMB:
High intensity muon bean
study ongoing
needed for Phase II
Mu3e: $\sim 10^9\ \mu^+/s$
PSI Goal: $\sim 10^{10}\ \mu^+/s$



Phase 1a Detector Design

Beamline Progress



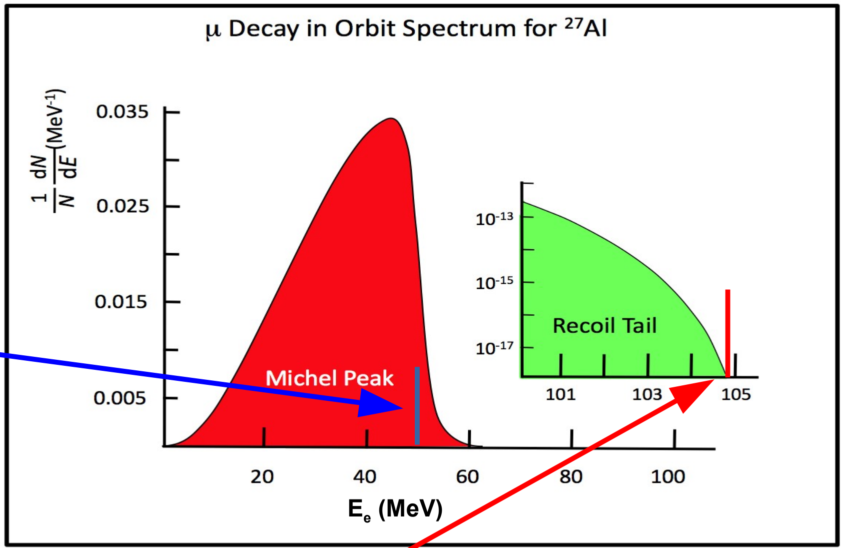
- muon beamline at PSI
- low energy DC beams
- πE5 beamline: $\sim 10^8$ 28 MeV/c surface muons
  - shared with MEG
  - works for Phase I → approved
- HiMB:
High intensity muon beam
study ongoing
needed for Phase II
Mu3e: $\sim 10^9\ \mu^+/s$
PSI Goal: $\sim 10^{10}\ \mu^+/s$

- staged approach and modular principle
  - Phase Ia: Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-14}$ (2016)
  - Phase Ib: Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-15}$ (2017)
  - Phase II : Sensitivity $\mathcal{B}(\mu \to eee) < 10^{-16}$ (2019)

μ A →e A Coherent Conversion

- Three different experimental designs & approaches:
  - Mu2e
  - Comet
  - DeeMe

Mono energetic e emission at endpoint of DIO spectrum



- Measuring:

$$\mathcal{R} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N(Z) \to \nu_\mu N(Z-1))}$$

$\mu^\pm \to \mathrm{e}^\pm \gamma$

MEG at PSI

$\mu^\pm \to \mathrm{e}^\pm \mathrm{e}^+ \mathrm{e}^-$

Mu3e at PSI

$\mu^- A(Z,N) \to \mathrm{e}^- A(Z,N)$

COMET at JPARC
Mu2e at FNAL

There are talks by all of these collaborations at this Workshop

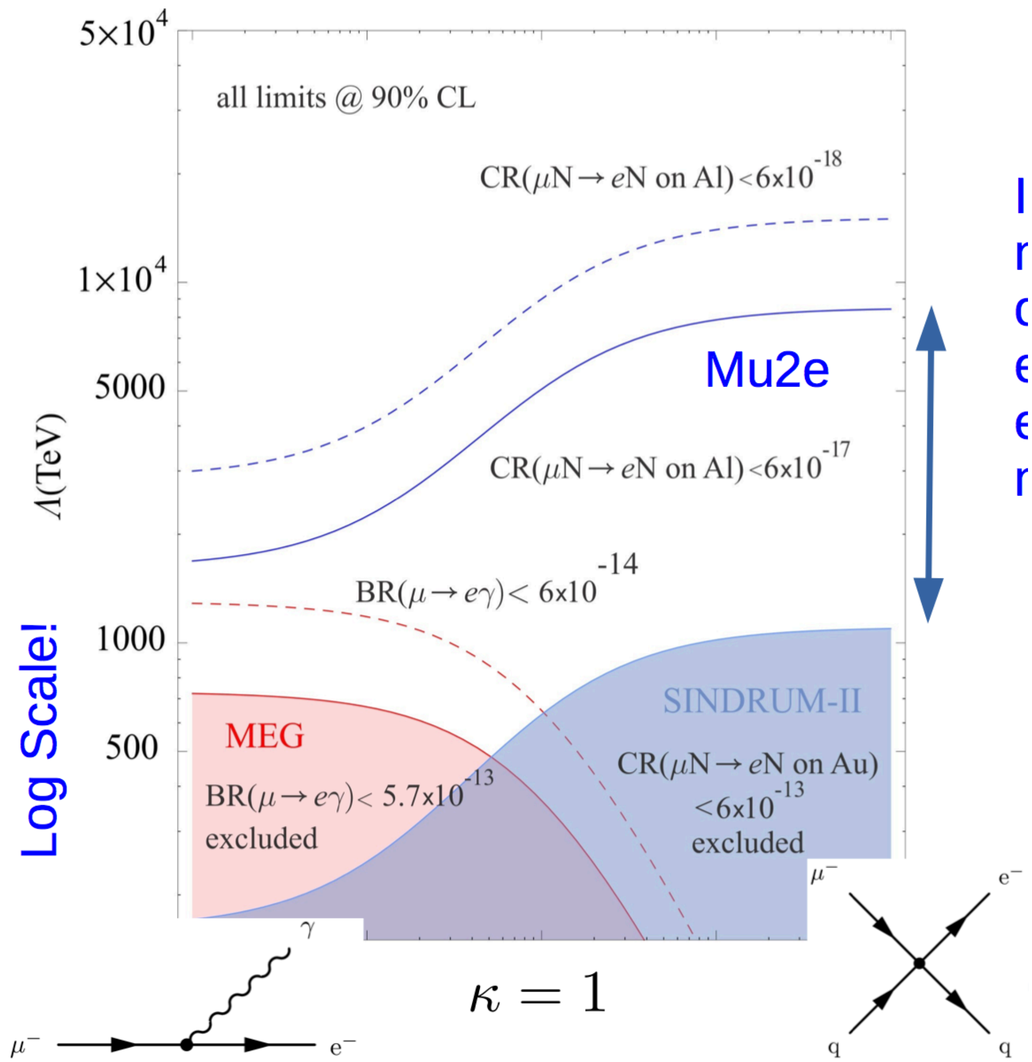
μ A →e A Coherent Conversion

- Three different experimental designs & approaches:
  - Mu2e
  - Comet
  - DeeMe

Probes to effective energy scales of 1000’s of TeV for BSM phyiscs

Highly complementary to $\mu \rightarrow e\gamma$

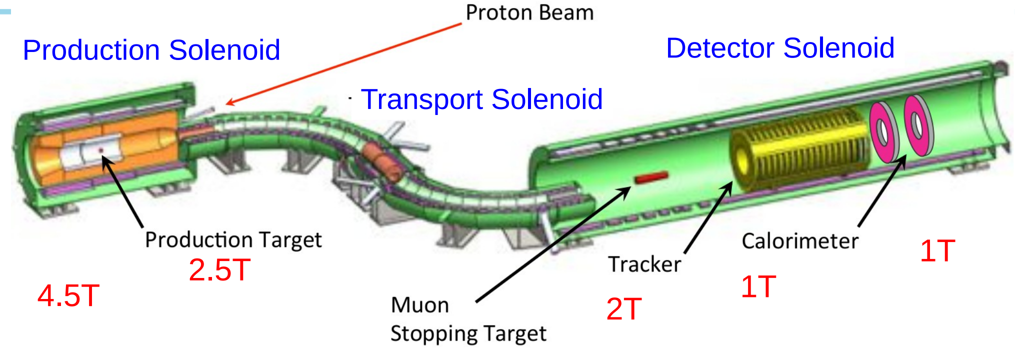
One of most effective probes for new physics

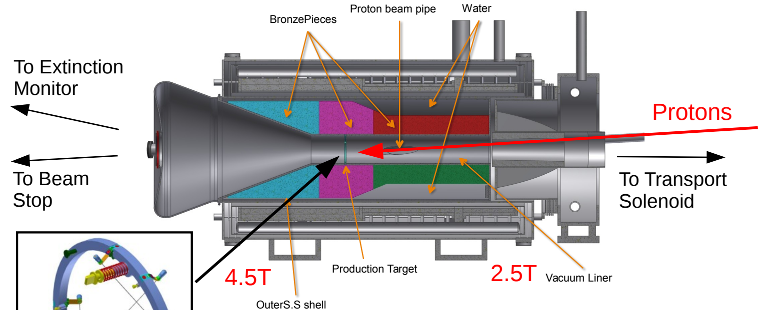


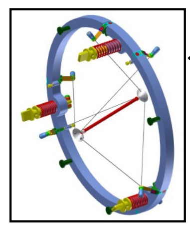
μ A $\rightarrow$ e A Designs

- Mu2e
  - Advanced detector and beamline designs
  - Forms part of core muon campus at FNAL

  - Sensitivities of 2.9×10^{-17}
  - First data in 2021

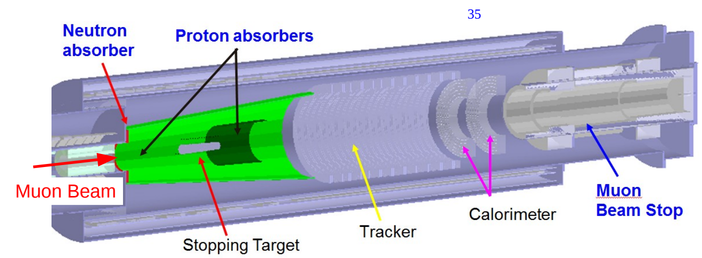


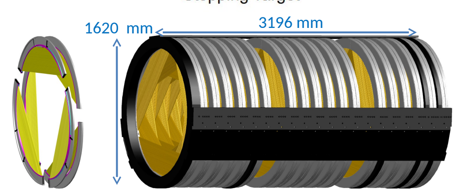




The tungsten production target is about the size of a pencil

The graded field acts as a “mirror” for charged particles, increasing the flux of muons into the TS





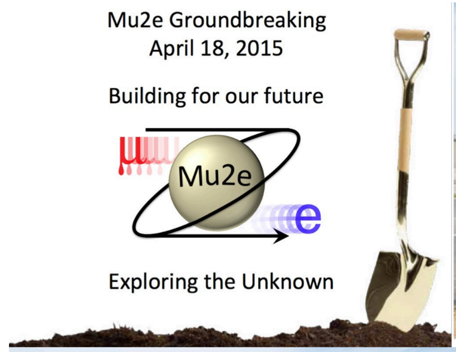
The electron tracker is a low mass straw tube design with 18 planes of tubes transverse to the secondary beam

39

K.Lynch

μ A $\rightarrow$e A Designs

- Under construction now

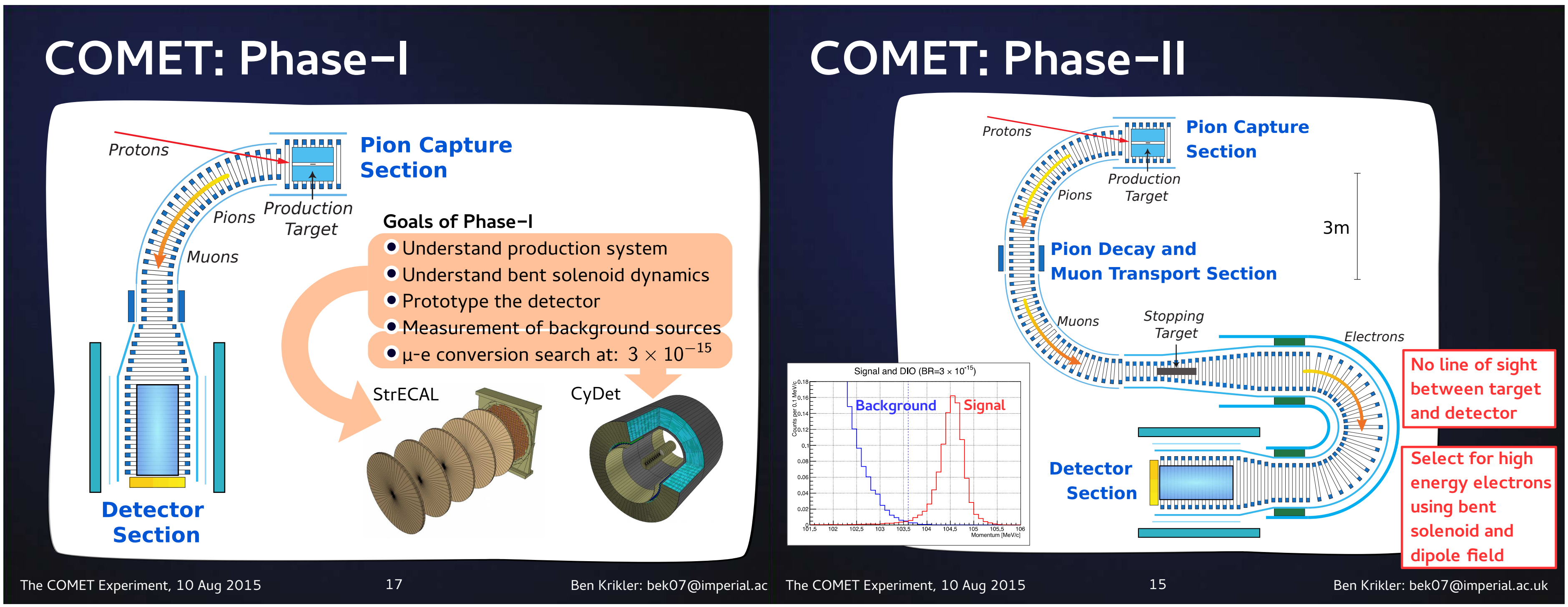


Fermilab

B.Krikler

μ A →e A Designs

- COMET
  - Phased approach to reach sensitivity of 3×10^{-17}
  - Early sensitivity at 3×10^{-15}
  - Advanced detector designs
  - Det. prototypes & some prod. components complete
  - Phase-I data in 2018/19



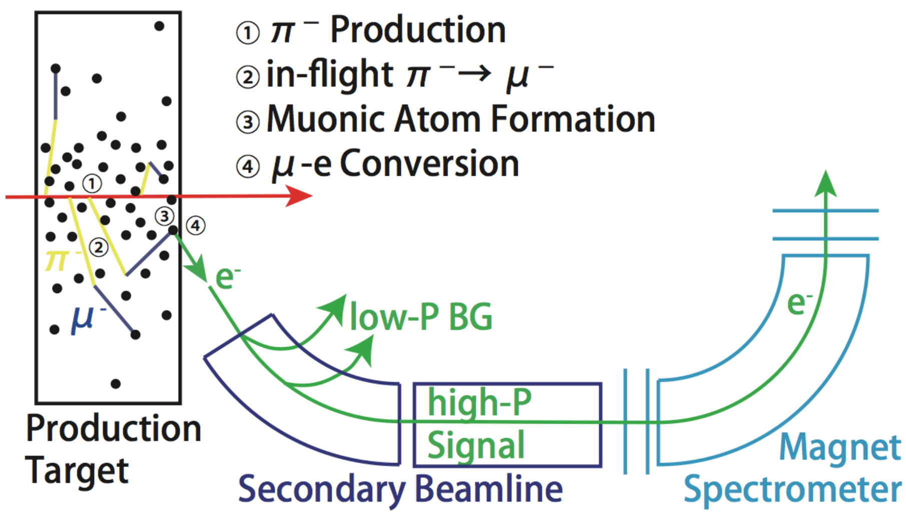
B.Krikler

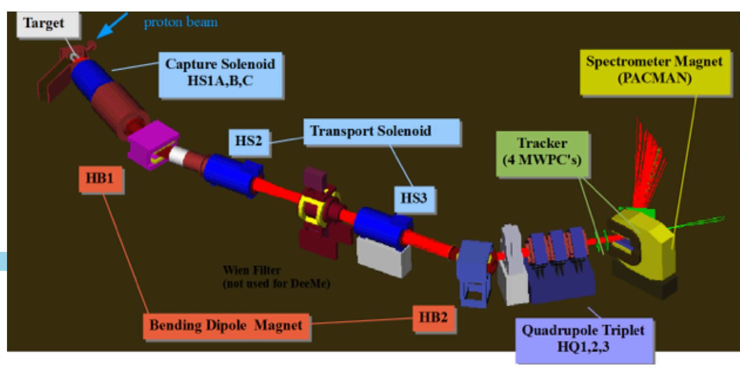
μ A →e A Designs

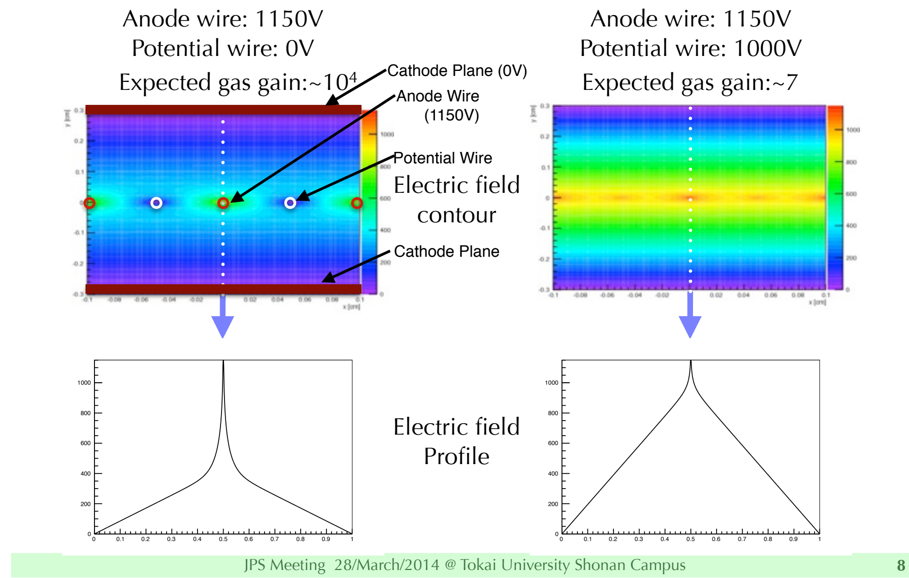
- Under construction now

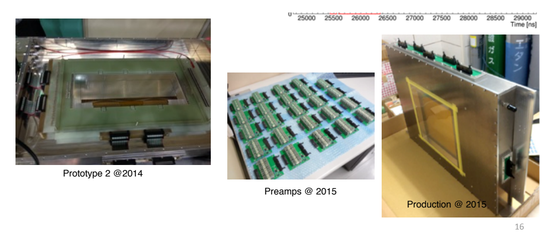
μ A →e A Designs

- DeeMe
  - Different approach uses beamline/spectrometer to momentum select signale e's
  - Designed to reach SES 2×10^{-14}
  - Gated MWPCs to suppress beam flash
  - Engineering run in 2016









Muon g-2

- One of the strongest probes for BSM physics
- Two very different approaches
  - FNAL g-2 uses “magic momentum” technique
  - J-PARC g-2 uses ultra cold muons and no electric focusing

BNL E821/Fermi

Magic momentum (p=3.1 GeV/c)

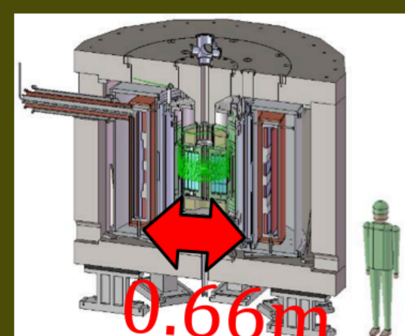
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

P=3.1 GeV/c
T=1.45 T

J-PARC

no electric focusing

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$



P=0.3 GeV/c
T=3.0 T

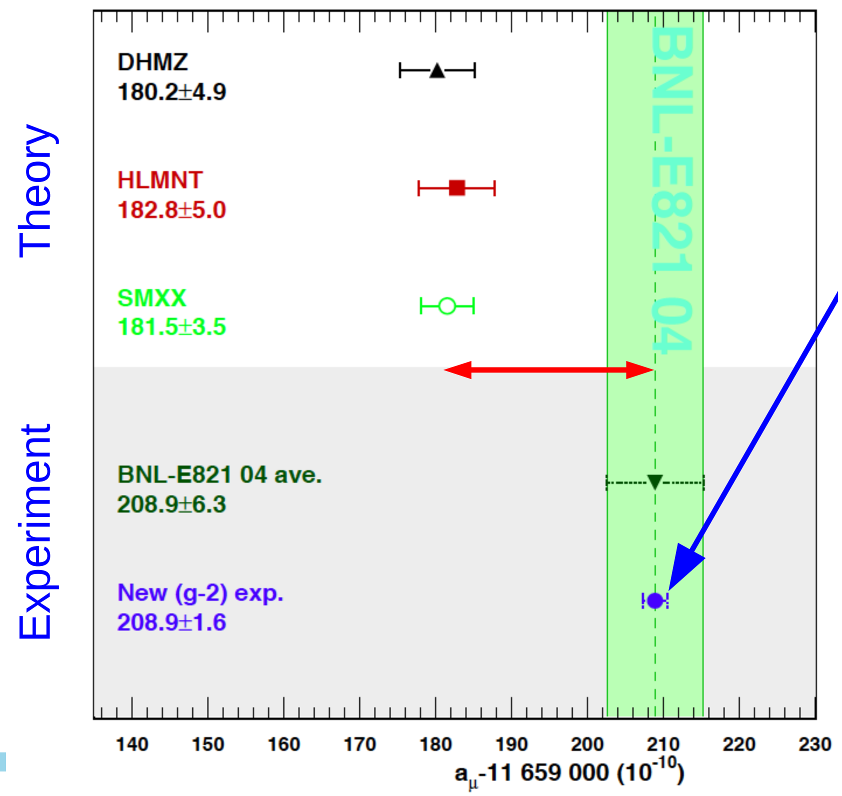
K.Lynch

FNAL Muon g-2

- Upgrade of BNL 821 to take advantage of FNAL beam complex + detector upgrades.
  - Uses same magnet (moved to Fermilab)
  - 4x improvement in statistical precision (0.54 ppm → 140 ppb)

Improvement over BNL 821

- New quadrupoles
- New kicker modules
- New absolute field calibration
- New trolley field calibration system
- New detectors to measure beam profiles
- New analysis algorithms
- More complete simulation framework
- New data acquisition hardware
- New data acquisition software
- New laser gain stabilization system

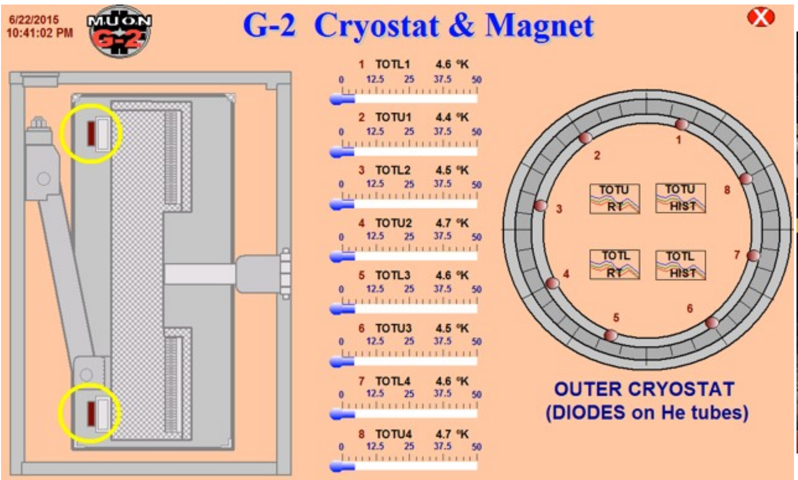


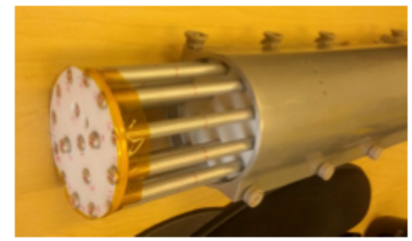

EMMERT
EMMERT

K.Lynch

FNAL Muon g-2

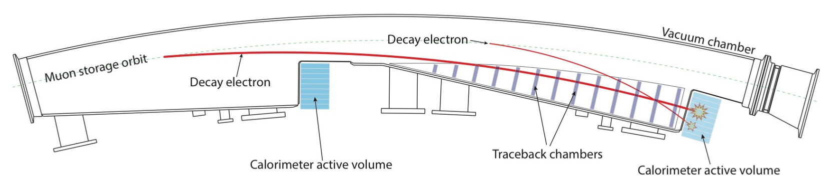
- Tremendous progress in ring re-commissioning & detector development
- First results expected 2018





New fixed and mobile field mapping probes

After 14 years, the ring has been cooled to superconducting temperatures and partially energized; some inevitable teething problems have been fixed, and the cooling should begin again on Monday

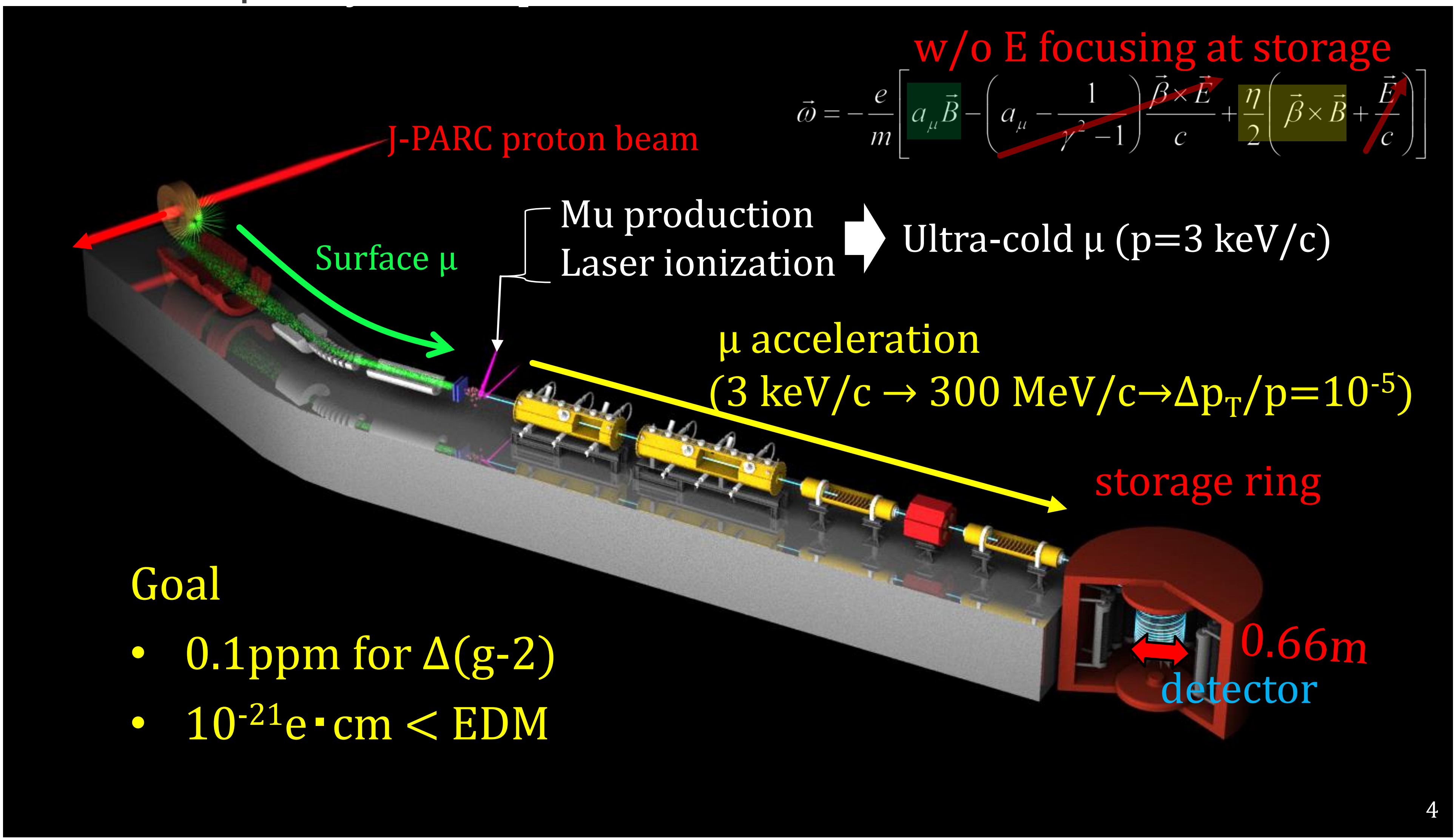


Three multiplane straw tracker systems will reconstruct the time-dependent muon decay position within the ring

M.Otani

J-PARC Muon g-2

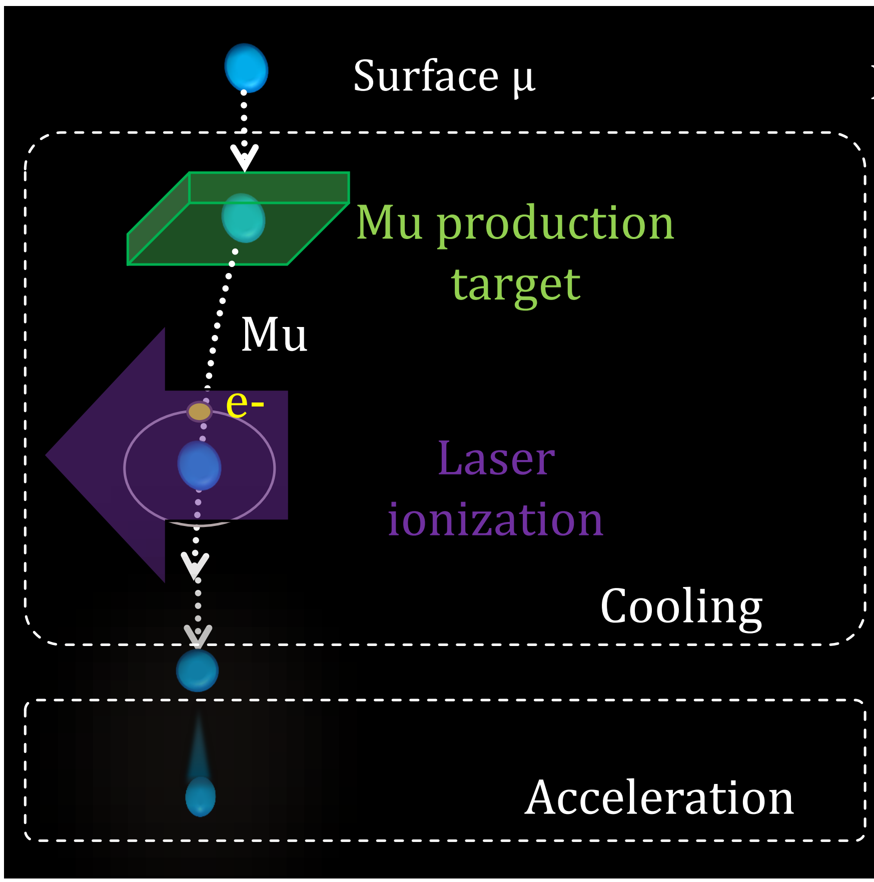
- Ultra cold muon beam technique
- Precision ~ 100 ppb

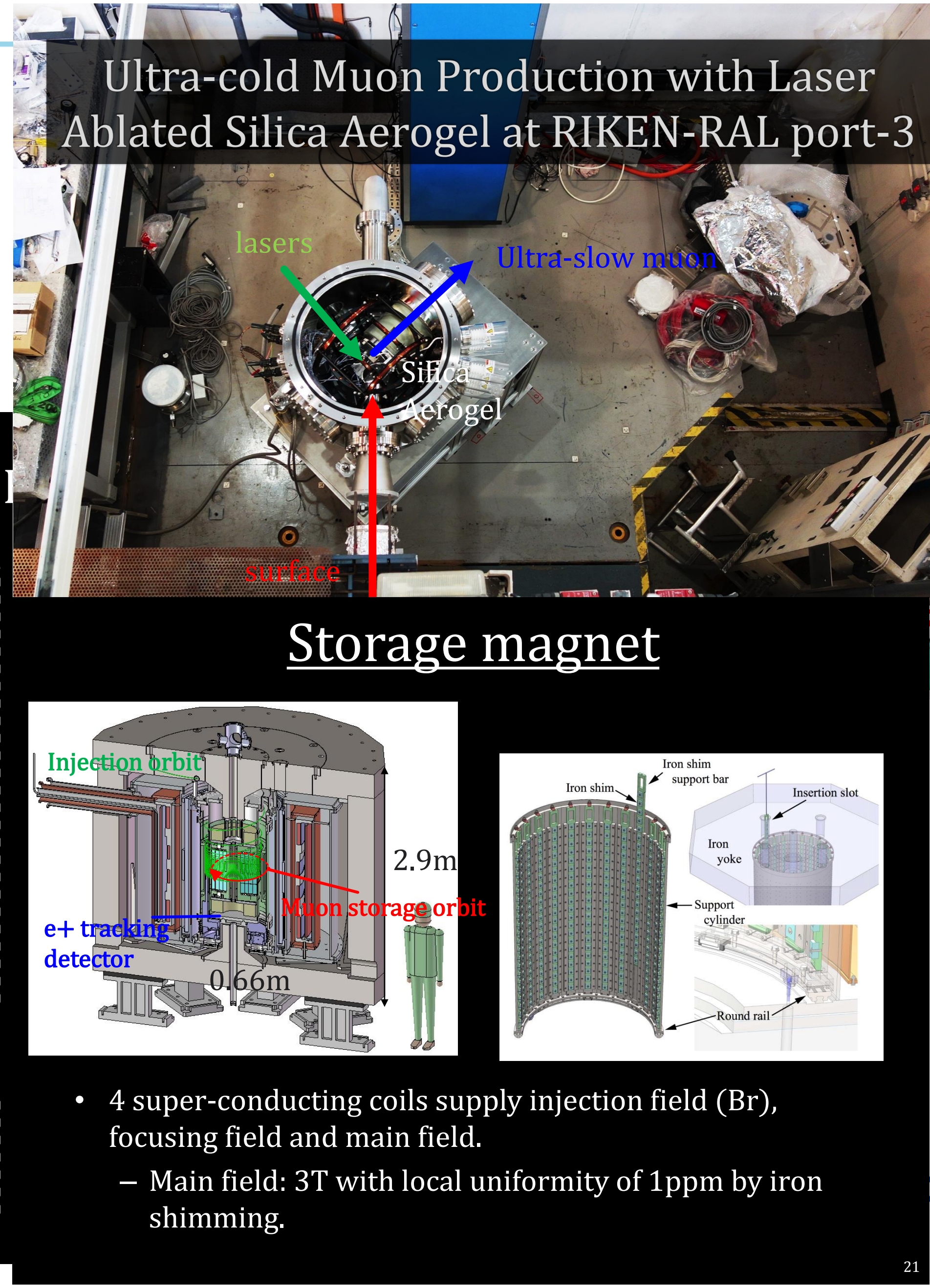


M.Otani

J-PARC Muon g-2

- Experiment enabled by cold muon accelerator designs.
- Permits small magnet with no efield





Questions Posed to NuFact 2015

- With the next generation of precision measurements experiments starting (muon g-2, mu to e conversion) <u>are there additional measurement which can be made to ensure their success or to improve their background estimates and expand their sensitivities?</u>

- Are there connections between cLFV searches and precision measurements which can be exploited to improve our progress in both regimes?

- How could a neutrino factory (and the supporting accelerator complex) be exploited to push our sensitivities for cLFV searches and precision measurements? Is there a secondary physics program that could be supported by such a complex which could address questions in both HEP and Nuclear Physics?

- What is the global picture that ties together “direct” and “indirect” for BSM physics? What are the results from the LHC and B-Factories telling us and is there a way to connect this sector with the next generation of precision measurements?

Other Measurements

- Mulan (muon lifetime)
- Mucap (muon capture on proton)
- Alcap (muon capture on Al)
- PiBeta/Pen (precision pion decays, rad. muon decay)

- nEDM
- NA61 (hadron yields)

- All of these measurements provide either sensitive probes for new physics, improve knowledge of systematics/backgrounds do both

K.Lynch

MuLan

- Precision muon lifetime measurement
- Extracts Fermi's constant

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left(1 + \Delta q^{(0)} + \Delta q^{(1)} + \Delta q^{(2)}\right)$$

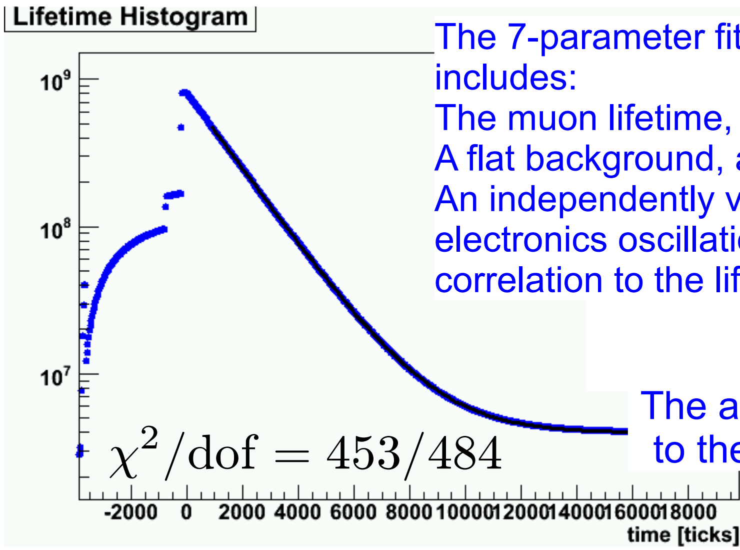
Phase space

First order corrections

Second order corrections

$$G_F^{\mathrm{MuLan}} = 1.166\,378\,7(6) \times 10^{-5}\,\mathrm{GeV}^{-2}$$

$0.5\,\mathrm{ppm}$



The 7-parameter fit functi
includes:
The muon lifetime,
A flat background, and
An independently validated electronics oscillation (with low correlation to the lifetime)

The analyzers ar
to the clock freq

MuLan Collaboration, Phys. Rev. Lett. 99, 032001 (2007)

MuLan was systematics limited … could we do better at a future facility?

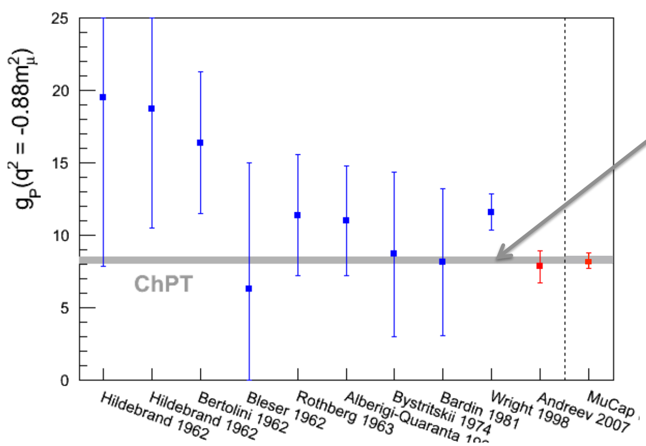
Uncertainty	R06 (ppm)	R07 (ppm)
Kicker stability	0.20	0.07
μSR distortions	0.10	0.20
Pulse pileup	0.20	
Gain variations	0.25	
Upstream stops	0.10	
Timing pick-off stability	0.12	
Master clock calibration	0.03	
Combined systematic uncertainty	0.42	0.42
Statistical uncertainty	1.14	1.68

My Verdict: Probably …

Mucap

- Muon capture on the proton
- Precision test of Chiral Perturbation Theory
- Measures g_p

Precise and unambiguous MuCap result confirms chiral perturbation theory prediction



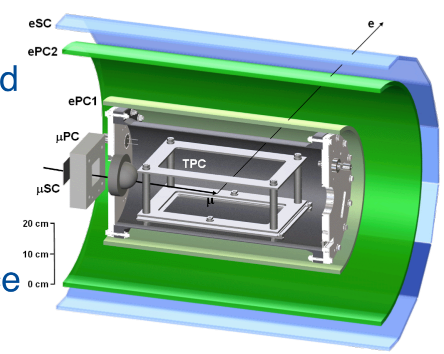
$\boxed{g_P(\text{MuCap}) = 8.14 \pm 0.55}$

Hadronic Current

$$J^\alpha = \bar{u}_n\left(\underbrace{g_V\gamma^\alpha + \frac{ig_M}{2m_N}\sigma^{\alpha\nu}q_\nu + \cancel{\frac{g_S}{m_\mu}}q^\alpha}_{V^\alpha}\ \underbrace{-g_A\gamma^\alpha\gamma_5 - \frac{g_P}{m_\mu}q^\alpha\gamma_5 - \cancel{\frac{ig_T}{2m_N}}\sigma^{\alpha\nu}q_\nu\gamma_5}_{A^\alpha}\right)u_p$$

- CVC + G-Parity
  - g_S , $g_T \approx 0$
- CVC + Electron scattering
  - $g_V(q_\mu^2) = 0.976 \pm 0.001$
  - $g_M(q_\mu^2) = 3.583 \pm 0.003$
- Neutron beta decay
  - $g_A(q_\mu^2) = 1.2497 \pm 0.004$
    - Propagate $g_A(0) = 1.2723 \pm 0.0023 \rightarrow q^2$
    - K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).
- This leaves g_P
  - Known with ≈50% uncertainty

- Use a low-energy muon beam
- Stop in a specially prepared pure hydrogen target
- Image the stopping muon (TPC)
- Measure the disappearance rate
- Compare to the positive muon lifetime (MuLan)

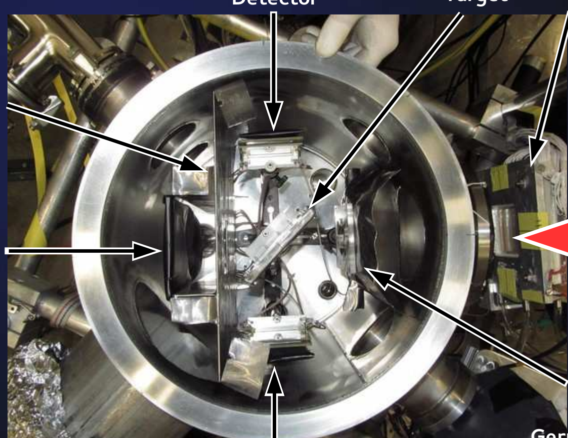


B.Krikler

Alcap

- Direct measurement of muon capture rate on AL
- Normalization for $\mu \rightarrow e$ conversion experiments
- Joint Mu2e/Comet exp

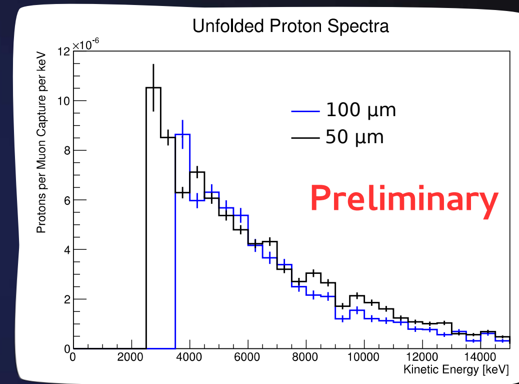
Run–1: Setup



AlCap, 12 Aug 2015 11 Ben Krikler: bek07@imperial.ac.uk

Run–1: Results (on–going)

So far:
- Proton Emission Spectrum from 3.5 to 10 MeV
- Proton emission per muon capture:
  - 0.020 (from 4 to 8 MeV)
  - 0.035 (integrated extrapolation)
  - Uncertainty about 9%



On–going:
- Deuteron, triton and alpha bands
- Final, combined proton emission rate

Impacts:
- COMET: Proton absorber removed
- Mu2e: Proton absorber re-optimised
- Changes to simulation code:
  - Vanilla Geant4 predicts about 30% of muon captures produce a proton
  - Fluka similar

AlCap, 12 Aug 2015 18 Ben Krikler: bek07@imperial.ac.uk

Run-2 under analysis
Run-3 scheduled for Nov. 2015

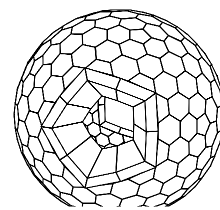
D.Pocanic

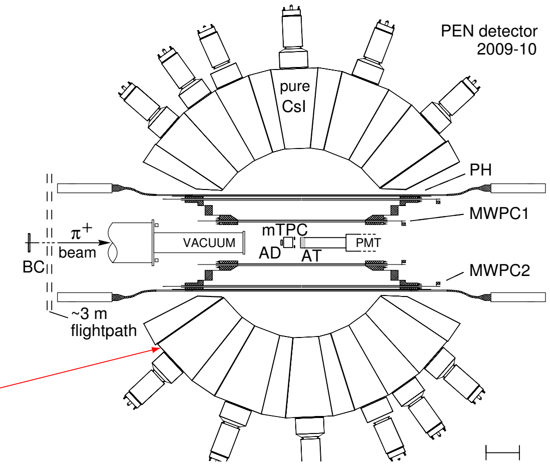
PiBeta & PEN

- Measurements of: $\pi_{e3}, \pi_{e2}, \pi_{e2\gamma}$ and radiative muon decay
- Precision tests of SM, CKM elements, lepton universality, BSM searches

The PIBETA/PEN apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity





Reach of π_{e2} decay beyond the SM (New Physics)

$$\mathcal{L}_{\rm NP} = \left[\pm\frac{\pi}{2\Lambda_V^2}\bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2}\bar{u}\gamma_\alpha\gamma_5 d\right]\bar{e}\gamma^\alpha(1-\gamma_5)\nu$$
$$+\left[\pm\frac{\pi}{2\Lambda_S^2}\bar{u}d \pm \frac{\pi}{2\Lambda_P^2}\bar{u}\gamma_5 d\right]\bar{e}(1-\gamma_5)\nu\,, \quad (\Lambda_i \ldots \text{scale of NP})$$

CKM unitarity and superallowed Fermi nuclear decays currently limit:

$$\Lambda_V \geq 20\,\text{TeV}, \qquad \text{and} \qquad \Lambda_S \geq 10\,\text{TeV}.$$

At $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} = 10^{-3}$, π_{e2} decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}},$$

and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

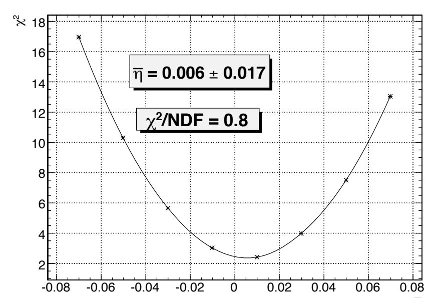
D. Počanić (UVa) Pion and muon decays: The π_{e2} decay 12 Aug '15

RMD preliminary results, cont'd.

Preliminary result for RMD branching ratio (thesis E. Munyangabe):

$B_{\rm exp} = 4.365\,(9)_{\rm stat.}\,(42)_{\rm syst.} \times 10^{-3}$, $\boxed{29\times}$

$B_{\rm SM} = 4.342\,(5)_{\text{stat-MC}} \times 10^{-3}$ (for $E_\gamma > 10$ MeV, $\theta_{e\gamma} > 30°$)



Analysis of PS subset:
13 MeV $< E_\gamma <$ 45 MeV, and
10 MeV $< E_{e^+} <$ 43 MeV, yields

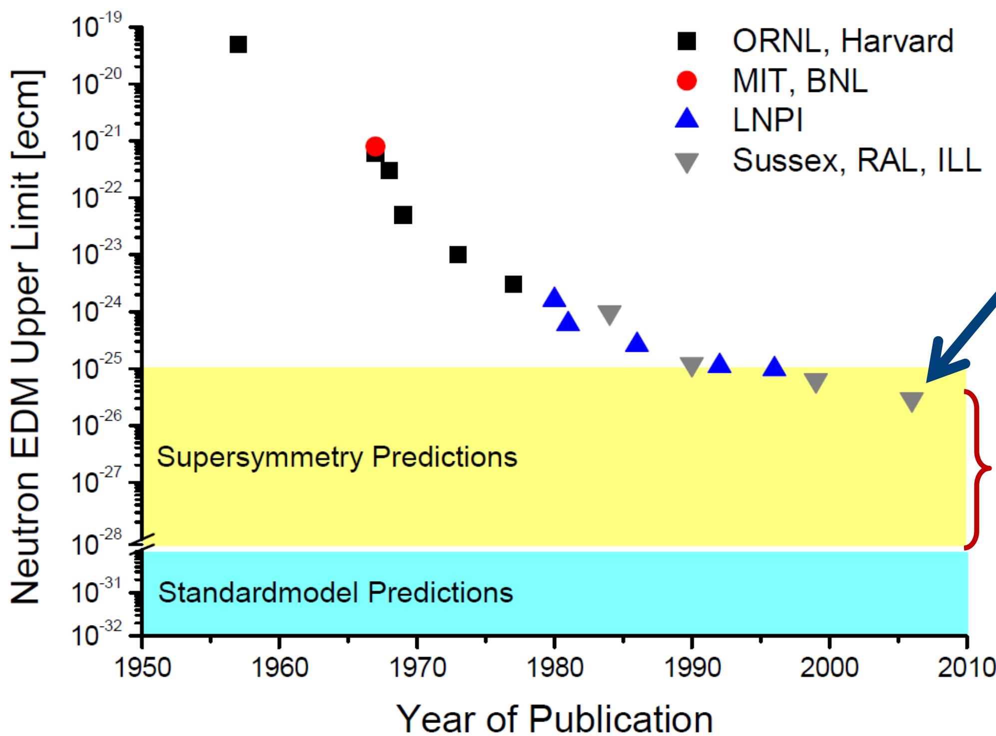
$\bar{\eta} = 0.006\,(17)_{\rm stat.}\,(18)_{\rm syst.}$, or
$\bar{\eta} < 0.028$ (68%CL).

$\boxed{\sim 4\times}$ better than best previous experiment (Eichenberger et al, 84).

NB: preliminary results!

D. Počanić (UVa) Pion and muon decays: Radiative muon decay 12 Aug '15 27/ 28

Neutron EDM



Best limit (2006)[2]:

$$d_n < 2.9 \times 10^{-26}\ \ e \cdot \mathrm{cm}$$
$$(90\%\ \mathrm{C.L.})$$

Excellent observable to constrain non-SM physics!

Standard Model prediction:

$$d_n \approx 10^{-32} \ldots 10^{-30}\ \ e \cdot \mathrm{cm}$$

(without QCD θ-term)

[2] Baker et al., PRL 97 (2006) 131801.

Our apparatus is functioning well:

- Sensitivity is excellent
- Systematic effect are under control $< 5 \times 10^{-27} e \cdot \mathrm{cm}$

We should reach $1.5 \times 10^{-26} e \cdot \mathrm{cm}$ by mid 2016!

Excellent (but beam limited) probe for BSM physics

Next stage is to build a new setup (n2EDM) which should be able to reach $3 \times 10^{-27} e \cdot \mathrm{cm}$

Questions Posed to NuFact 2015

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- Are there connections between cLFV searches and precision measurements which can be exploited to improve our progress in both regimes?

- How could a neutrino factory (and the supporting accelerator complex) be exploited to push our sensitivities for cLFV searches and precision measurements? Is there a secondary physics program that could be supported by such a complex which could address questions in both HEP and Nuclear Physics?

- What is the global picture that ties together "direct" and "indirect" for BSM physics? What are the results from the LHC and B-Factories telling us and is there a way to connect this sector with the next generation of precision measurements?

Looking Forward

- Muon physics program is transitioning in the questions being asked
  - No longer design questions
  - More complementarity/synergy questions with existing & future programs/facilities

- Starting new era where a convergence of new results is on horizon
  - LHC 14 TeV, Super-B Factories, g-2 and phase 1 mu2e's and nEDMs all may have new information in the next 5 year
  - May be able to start strongly constraining the BSM sector

New Questions

- Neutrino/Muon Physics:

  "What overlaps exist in non-standard interactions? How would these manifest in both the near term muon/precision measurements sector & in the neutrino sector?"

- Beam/Machine Design:
  - "How can you improve experiments with out increasing the beam power? Cooled muon beams w/ phase rotations? New methods?"

- Program Planning:
  - "How do you support the physics needs for both DC and pulsed (high sculpted) beam structures in the planning (and cost) of new facilities?"

Fermilab

- Obrigado!

  for a very successful NuFact!